Stellar Flare Dynamics from High-Resolution X-ray Spectroscopy

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Abstract

Stellar flares on cool stars are a ubiquitous phenomenon in the X-ray spectral region. This most dynamic aspect of coronal activity is possibly a primary source of coronal heating. On the Sun, flares are known to be a manifestation of the reconnection of magnetic fields and are accompanied by particle beams, chromospheric evaporation, rapid bulk flows, mass ejection, and heating of plasma confined in loops. Modeling the dynamic behavior allows us to constrain loop properties in ways that cannot be done from analysis of quiescent coronae that necessarily require a spatial and temporal average over some large ensemble of structures. Hard X-rays (7-20 keV) cause Fe K fluorescence whose presence and time profile can also be a powerful diagnostic of flare loop geometry.

The International X-Ray Observatory (IXO) promises unprecedented advances in effective area and resolution for X-ray spectroscopy. We present simulations to explore opportunities IXO might offer for studying high-energy dynamics in the outer atmospheres of stars. In particular, we will explore the ability to obtain time-resolved spectral diagnostics from flares of cool, coronally active stars. We expect IXO to obtain both quantitative improvements (more sources, better sensitivity) and qualitative advances (new constraints on hydrodynamic models).

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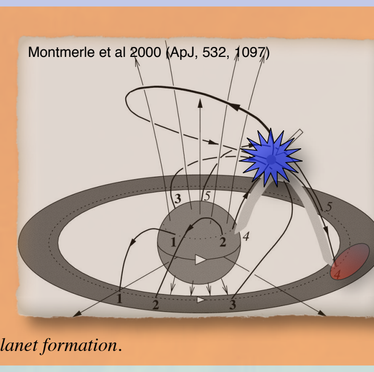
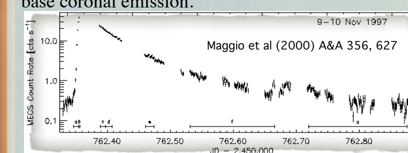
Why study stellar flares with IXO high resolution spectrometers?

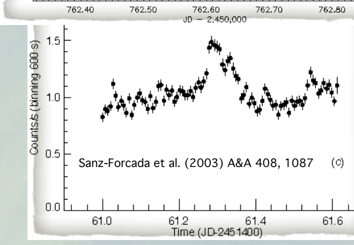
- ★ enough sensitivity and resolution to study *distributions* of flare properties;
- ★ use powerful new diagnostics *routinely* (e.g., Fe K fluorescence, line profiles, and line shifts);
- ★ probe *non-equilibrium* plasma states through flare evolution;
- ★ constrain the role of loops and reconnection in the *angular momentum evolution of proto-stellar disks*;
- ★ study the effects of X-ray flare irradiation on circumstellar *disks and planet formation*.



Plasma models: To generate model spectra, we used the Astrophysical Plasma Emission Database (APED/APEC; Smith et al 2001 ApJ 556, L91) with APEC density dependence for the He-like triplets (Smith et al 2002; `cxc.harvard.edu/atomdb/features_density.html`), and integrated the flare model over time intervals. During the initial heat pulse we assumed a bulk velocity of -100 km/s. We assumed a broken powerlaw emission measure distribution (EMD) for the flare plasma, rising to the peak temperature of the model, with a very sharp cutoff, similar in form to flare EMD reconstructions of Reale et al (2004 A&A 416, 733) for Proxima Cen.

Stellar flares come in many shapes and sizes. Below are two examples for **AB Dor**, a single, rapidly rotating (P=0.5d), very active (f_x~3x10^{-11} ergs/cm^2/s) and nearby (14.9 pc) G-star. Our simulations adopt an AB Dor-like medium flare with a increase of about 10 times over the base coronal emission.

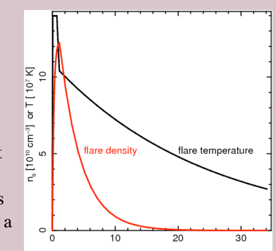


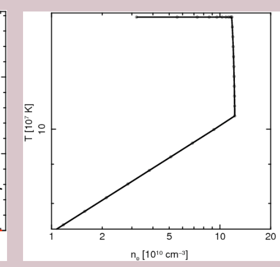


The IXO Instrument Model: To simulate IXO spectra, we have adopted a model instrument which includes a **Critical Angle Transmission (CAT) grating spectrometer** which covers part of the mirror aperture and provides about **1000 cm²** **effective area** from 0.3-1.0 keV at a **resolving power of about 3000**, as read out by a CCD array. The combined transmitted zeroth order and direct beam can be *simultaneously* imaged onto a **calorimeter with a resolution of about 2.5 eV with an effective area of 1-2 x 10⁴ cm²** from 0.6-6 keV. We used realistic efficiencies for mirrors, detectors, and gratings, and adopted a Lorentzian profile for the CAT grating and Gaussian for the X-ray Microcalorimeter System (XMS).

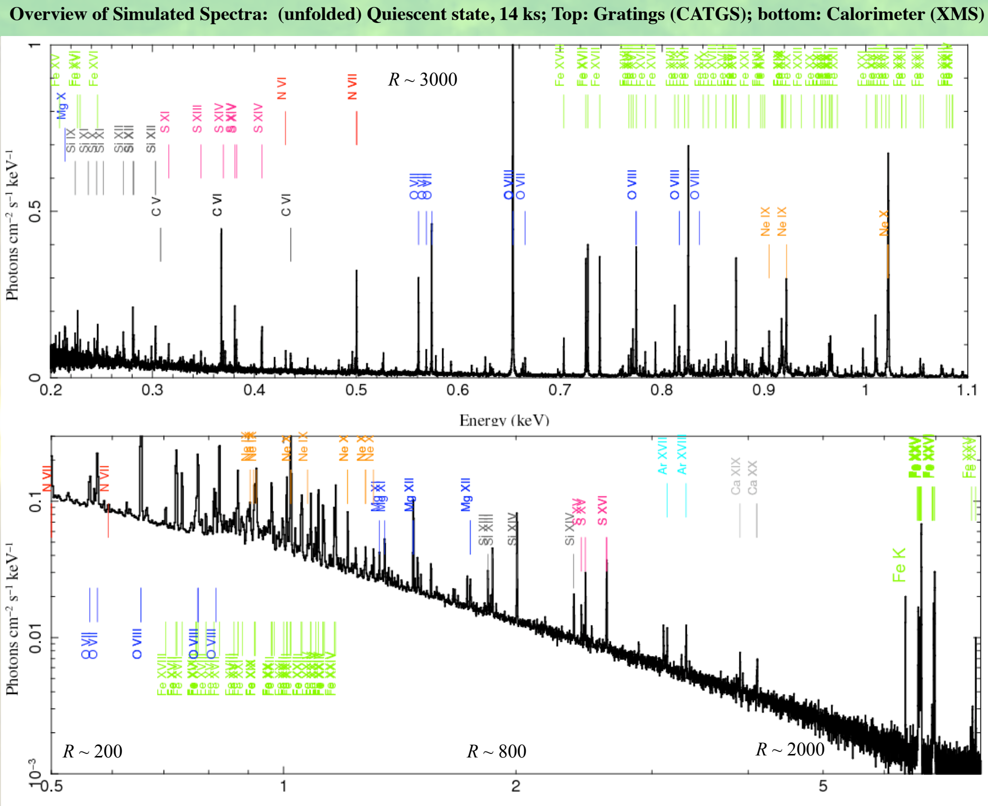
Simulation and modeling were done in ISIS, the Interactive Spectral Interpretation System (`space.mit.edu/cxc/software/isis`; Houck and DeNicola 2000, ASP Conf., 216, 591) using response matrices to define the instrumental performance. Prototype response matrices are available at `space.mit.edu/home/dph/ixo`.

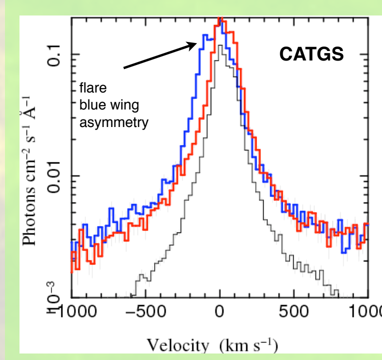
Flare models: We use the theoretical foundation of Reale (2007; A&A 471, 271) which describes rise and decay of a single-loop flare, defined by a heating pulse duration, maximum temperature, and loop size. A density profile with time defines the emission measure evolution for constant volume. Reale (2007) gives parameters for the AB Dor flare observed by Maggio et al (2000). The figures show our adopted temperature and density evolution. Our peak emission measure was 5x10^{53} cm^{-3} with a constant coronal emission measure a factor of ten lower, such as observed with Chandra by Sanz-Forcada et al (2003). Peak and quiescent fluxes were about 40 x 10^{-11} and 3 x10^{-11} ergs/cm^2/s.

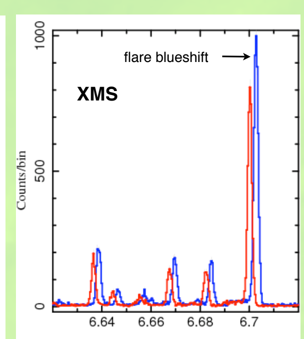




Overview of Simulated Spectra: (unfolded) Quiescent state, 14 ks; Top: Gratings (CATGS); bottom: Calorimeter (XMS)

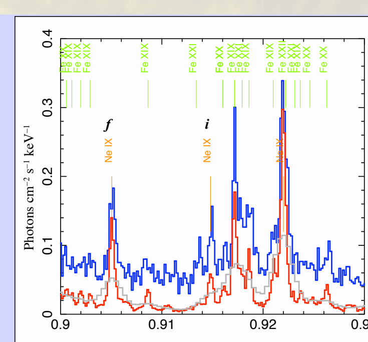


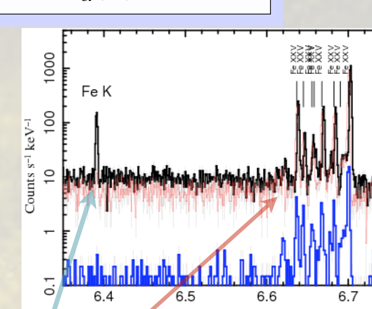




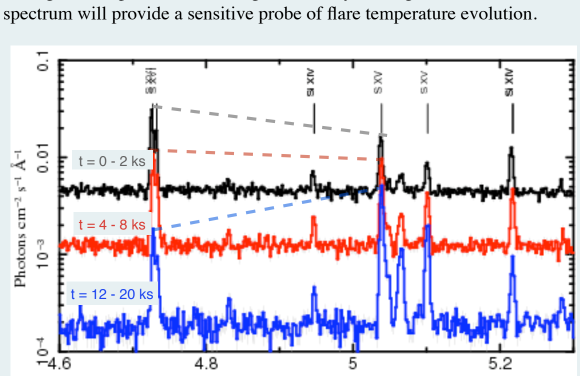
Dynamics: High spectral resolution allows us to probe bulk and turbulent flows in the hot flare plasma as well as in the cooler corona. Our flare model imposed a 100 km/s flow during the initial thermal pulse (t<2ks), and this is easily seen in the Fe XXV lines (near left): blue is for t = 0-2ks, and red is 2-4 ks. At the far left is O VIII for the same times as well as later times (gray). The oxygen lines show asymmetries since the model had a small amount of cooler plasma in the flare.

Flux density in the **Ne IX He-like triplet** region. At these energies, the grating (blue - flare; red - quiescent) has significantly higher resolving power than the calorimeter (gray). The Ne IX forbidden (*f* ,13.70A, 0.905 keV) to intercombination (*i*, 13.55A, 0.915 keV) line ratio is an important density diagnostic. Also available in the spectra for coronal density diagnosis are Mg XI (9.2A, 1.35 keV), O VII (22A, 0.56 keV), N VI (29A, 0.43 keV), and C V (41A, 0.30 keV).

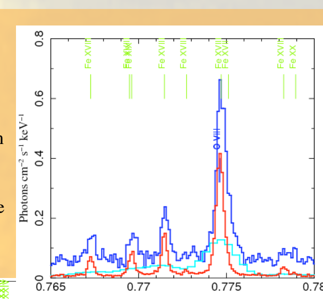


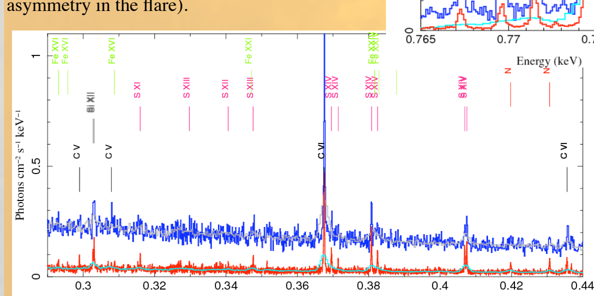


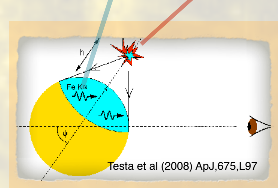
Temperature diagnostics: The He-like to H-like line ratios are temperature sensitive. Below are the S XVI and S XV resonance lines (from XMS) for three intervals during the flare: 0-2 ks (black), 4-8 ks (red) and 12-20 ks (blue). Other ratios are sensitive to higher temperatures (Ar, Ca) and some to lower (Si, Mg, Ne, O). The high energy continuum is also a very good diagnostic of the highest temperatures. The high sensitivity and high resolution across the spectrum will provide a sensitive probe of flare temperature evolution.



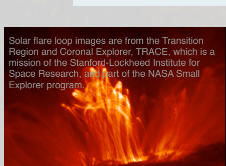
These plots show some details for the CATGS spectrum during the impulsive phase (first 2 ks, blue) and the late stage quiescence (14 ks, red). The light lines show the XMS spectrum. This demonstrates the need for using *both* the XMS and XGS to obtain *simultaneous* high-resolution spectral diagnostics across the spectrum, for both high and low temperature features, density dependence (e.g., C V lines) and dynamics (note the 0.775 keV (16 A) O VIII + Fe XVIII asymmetry in the flare).







Line detail in the **Fe K, Fe XXV region**. The flare peak, 0-2ks, is in black. Red is 2-4 ks, and blue is from 12-20 ks. Flare illumination of the photosphere with photons of E > 7 keV can cause Fe K fluorescence. The yield depends upon the flare height and photospheric Fe abundance. We assumed a yield of 2% to model Fe K, which fades extremely rapidly vanishing by 3ks in this model. IXO can provide detailed tests of flare geometry.



Conclusions: The IXO large throughput combined with high resolving power grating and imaging spectrometers together will make a powerful instrument for time-resolved studies of flares in cool stars. Measurements of density, temperature, velocity throughout a flare *rise and decay* at high resolution from 0.3 to 7 keV will provide critical tests of flare loop hydrodynamic models.